

Managing Complexity In Grid Operations

Lessons Learned from Recent Events



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Overview

Context: Increased Complexity in Grid Operations

What and Why: Recent Events

- Iberian Blackout
- Chile Blackout
- Other Events (Nth Macedonia, US Large Load)

What Next: Lessons Learned and Future Needs



Context: Complexity in Grid Operations

The Grid is Becoming Much More Complex to Operate



Key Challenges with the Changing Grid

Electric Vehicles, Data Centers,
Crypto mining, H₂ Production,
New Manufacturing, Heating
Electrification, ...

Wind and Solar Generation,
Aging Transmission
Infrastructure, Climate impacts
...



Consider Operators or Planners Trying to Solve Grid Problems

In the yellow mode they try to “make sense”

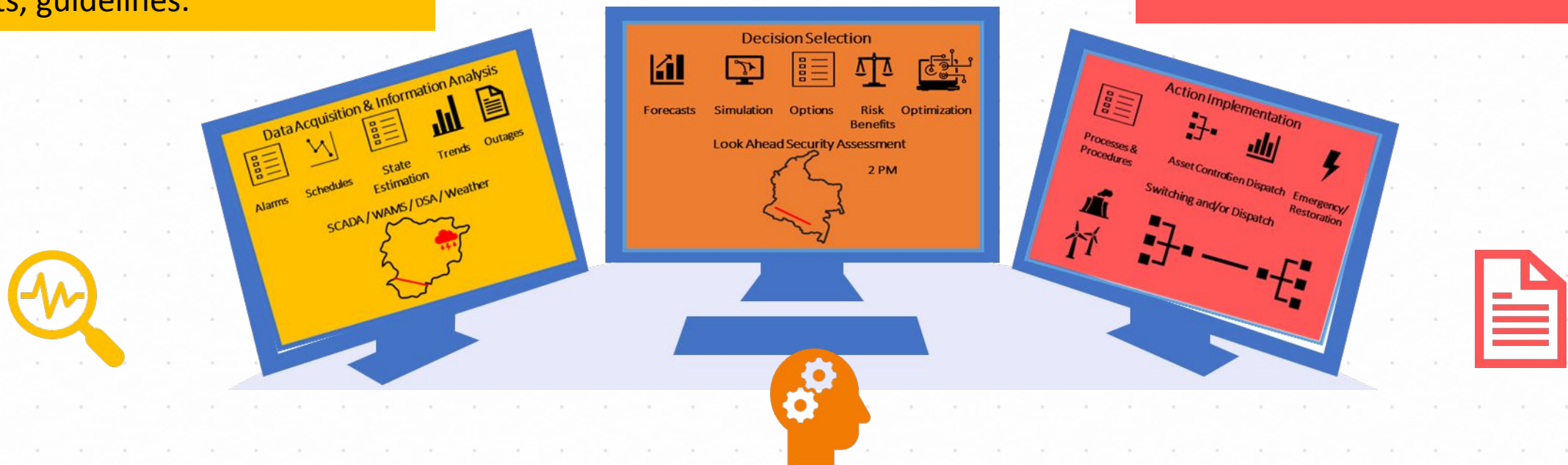
- **Operators:** try to decipher alarms, oscillations, trends, weather, prices
- **Planners:** try to curate and validate models for studies based on best available input parameters, read reports, guidelines.

In the orange mode they “make decisions”

- **Operators:** forecast, simulate, optioneer, risk assess, evaluate, optimize, decide
- **Planners:** have similar activities but on a longer time-frame.

In the red mode they “make actions”

- **Operators:** is switching, redispatch, report writing, phone calls to field crew.
- **Planners:** write summary reports, planning permits, cost benefits, codes and standards etc

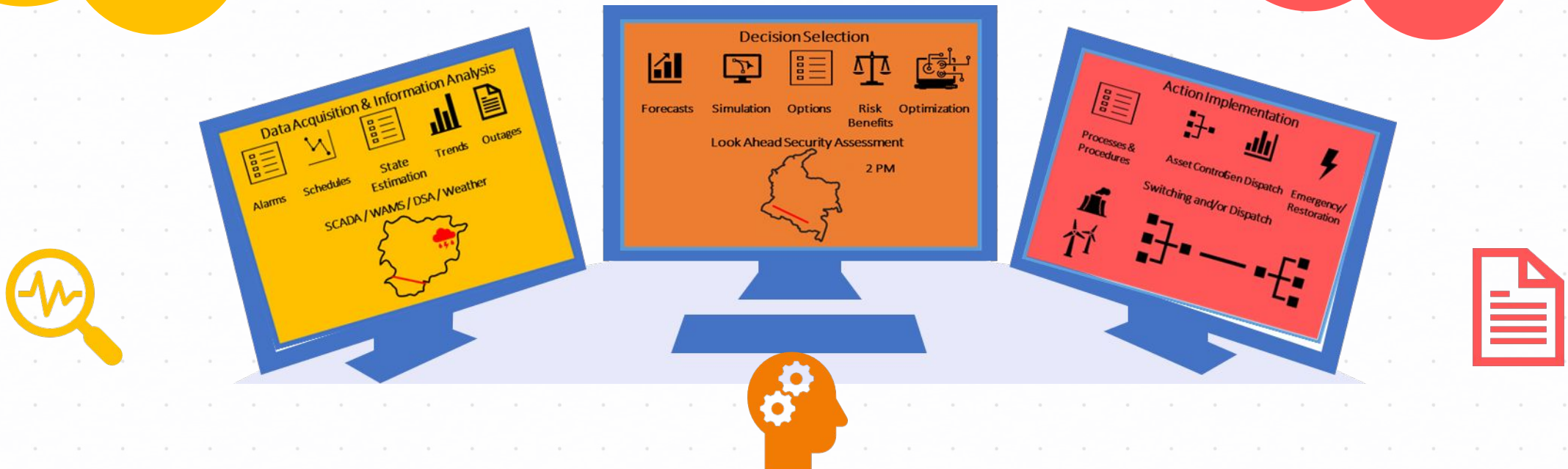


How are these Three Modes Being Impacted Today?

Too much data,
Too many systems,
Fragmentation and
interconnection of networks,
New assets,
Digitisation of assets,
New market participants,
Major Weather events.

Multi factorial decision making,
Interconnected network entities,
New markets, services
New challenges, Less experience,
Variable resources, need to forecast “look
ahead” capability
New operating modes,
New network phenomena

More reporting, administration,
Protection/control automation
interventions,
More assets to operate,
More planned/unplanned outages
More resources to be controlled
Safety procedures,
Planning permits



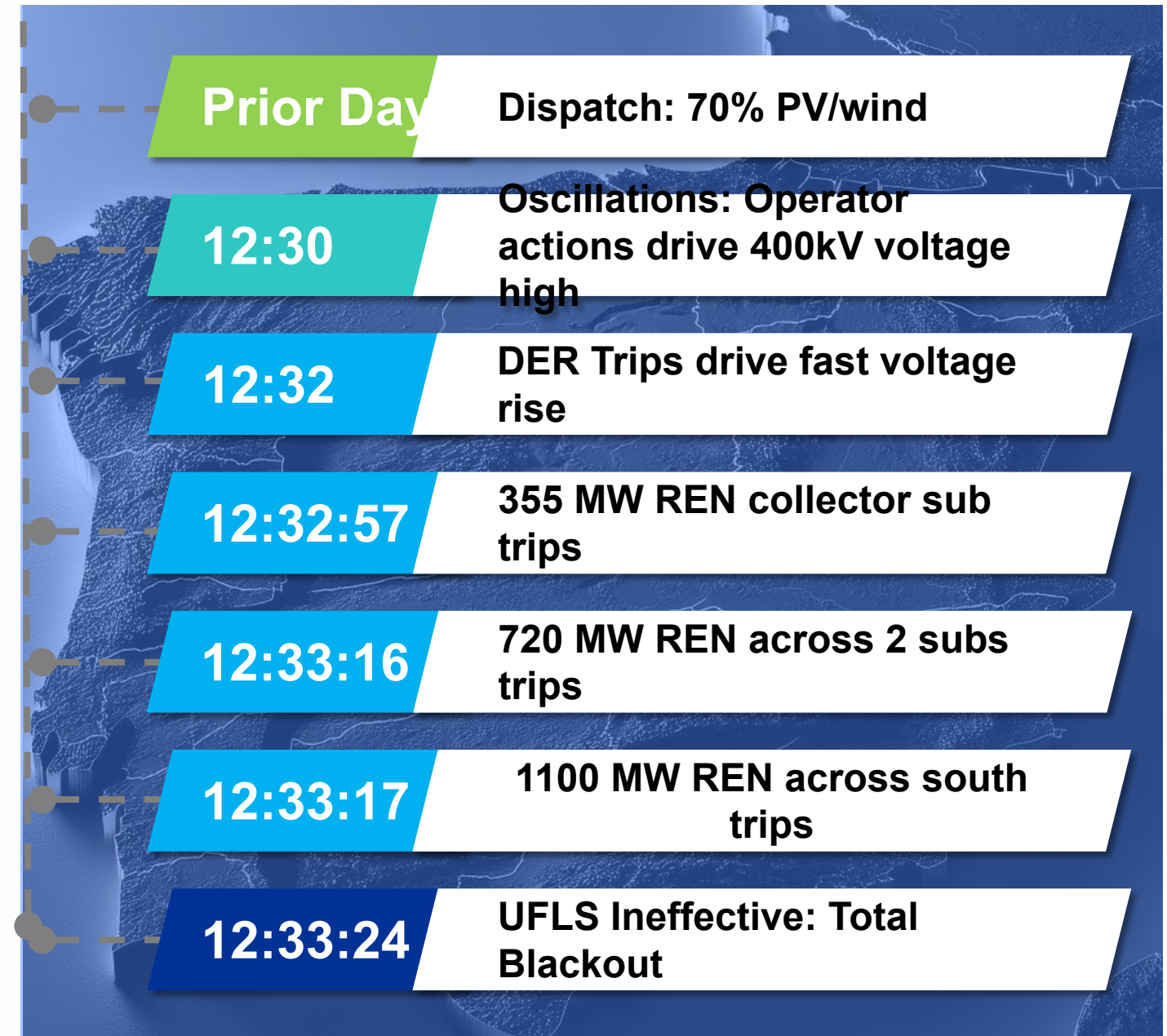


What and Why: Recent Events

2025 Iberian Peninsula Blackout

How Risk Drivers Converged

On April 28th a resource dispatch and oscillations drove a complex operating scenario that cascaded **into a total blackout within 27 seconds** of the first HV network trip.



Anatomy of the Iberian Blackout

Misalignment of Regulation and Markets



IBR-heavy resource mix with limited reactive support (PF control); out-of-market actions for local voltage control, and no ramp rate limits

Operating Processes/Tools for Complex Conditions



Operating decisions to mitigate oscillations exacerbated steady-state bus overvoltages that were approaching limits

Resource Performance and Grid Code Compliance



Some generators may have tripped below overvoltage ride-through level and may not have provided required reactive support

Protection Coordination for Complex Conditions

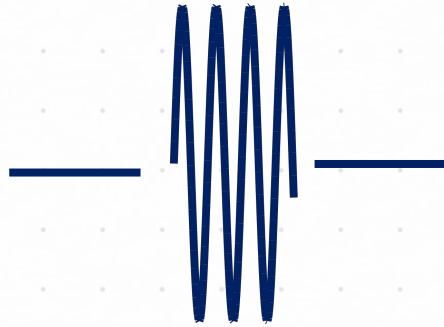


UFLS operation to arrest frequency decline tripped load and distributed resources, accelerating overvoltage cascade

Many factors converged leading to the **overvoltage-driven** Iberian Blackout, indicative of the multi-variable **risk in operating increasingly complex grids**.

Conflicting Operator Actions in Off-Normal Conditions

Oscillation Mitigations

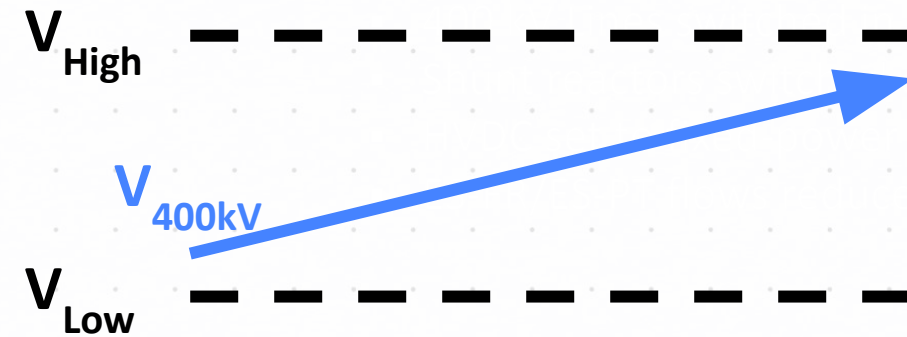


Switch in 400 kV lines

Reduce export to France

Reduce PV Generation

400 kV Voltage Impact



Stronger grid increases voltage

Reduced flow increases voltage

Reduced reactive absorption increases voltage

Operators need more automated, intelligent controls during off-normal conditions

Regulation & Markets Set Context for Voltage Risk

R

Distributed Renewables □ light loaded 400 kV grid prone to overvoltage

R

Renewables in Spain limited by regulation in ability to control voltage

M

Energy markets clear renewables before resources providing voltage control

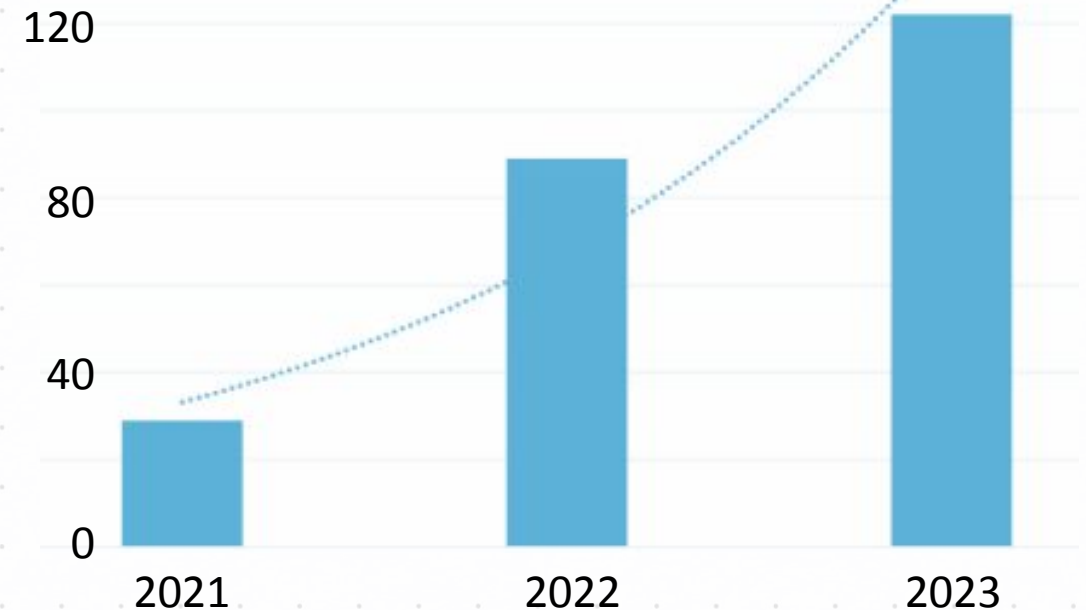
R

Regulation Outcome

M

Market Outcome

Number of power plants tripped by overvoltage protection in Spain increasing yearly

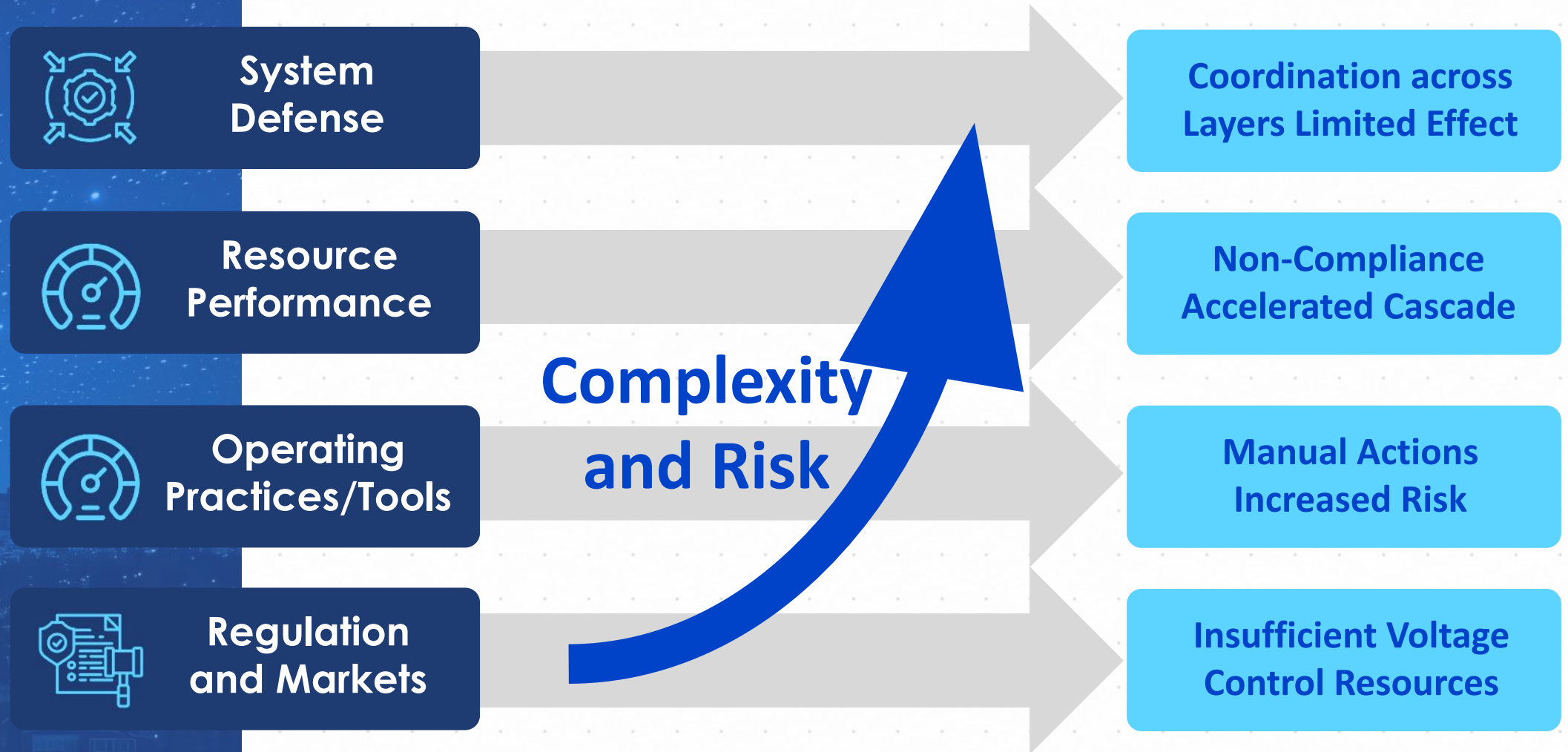


[PO_resol_10mar2000_correc.pdf](#) P.O. – 7.4

<https://www.boe.es/buscar/act.php?id=BOE-A-2007-10556> Real Decreto 661/2007, de 25 de mayo, por el que se regula la actividad de producción de energía eléctrica en régimen especial

CIGRE Jornadas Técnicas, 2023, PABLO MARTÍNEZ-FRESNEDA CERECEDA, REE

Many Factors Drove Grid Complexity that Led to Blackout



North Macedonia 18th May 2025

Similar Voltage Related Issues

Overvoltage related blackout

Sunday morning

Prior to the blackout:

- unusually high voltages were observed
- very low consumption and
- very low cross-border transfers

Voltage management

- Ratio of generation – transmission assets

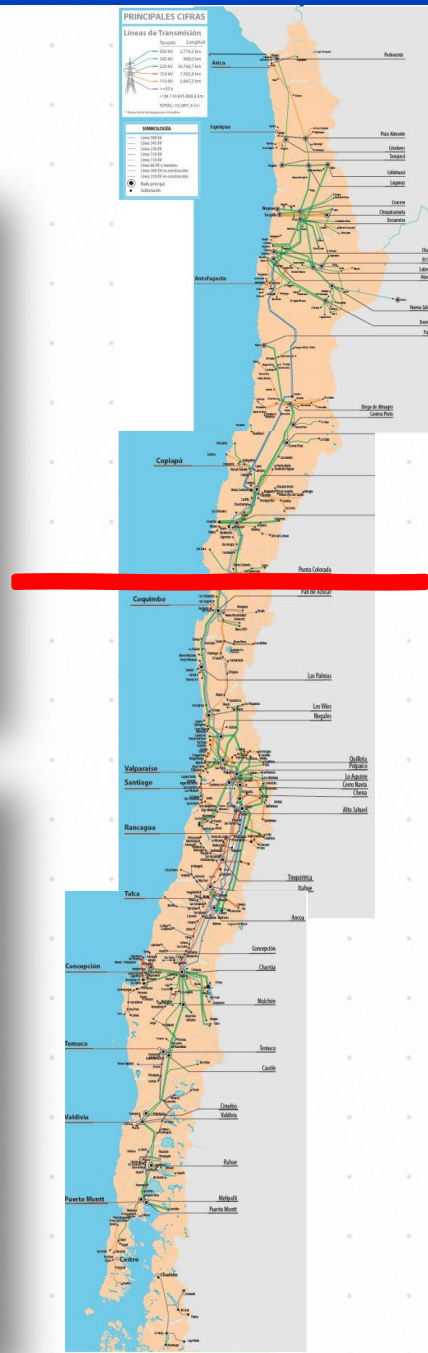
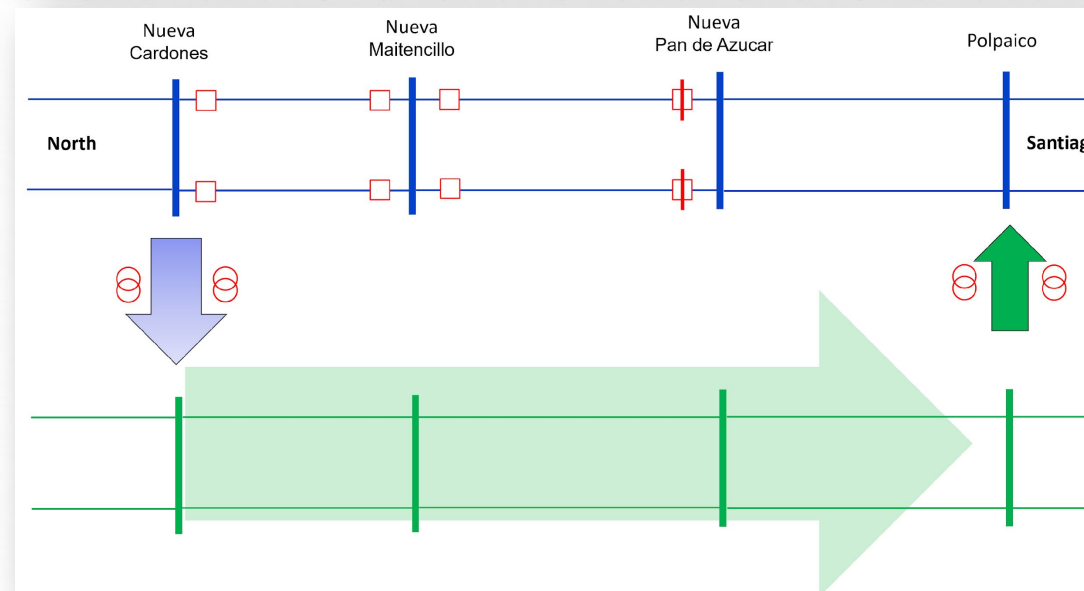
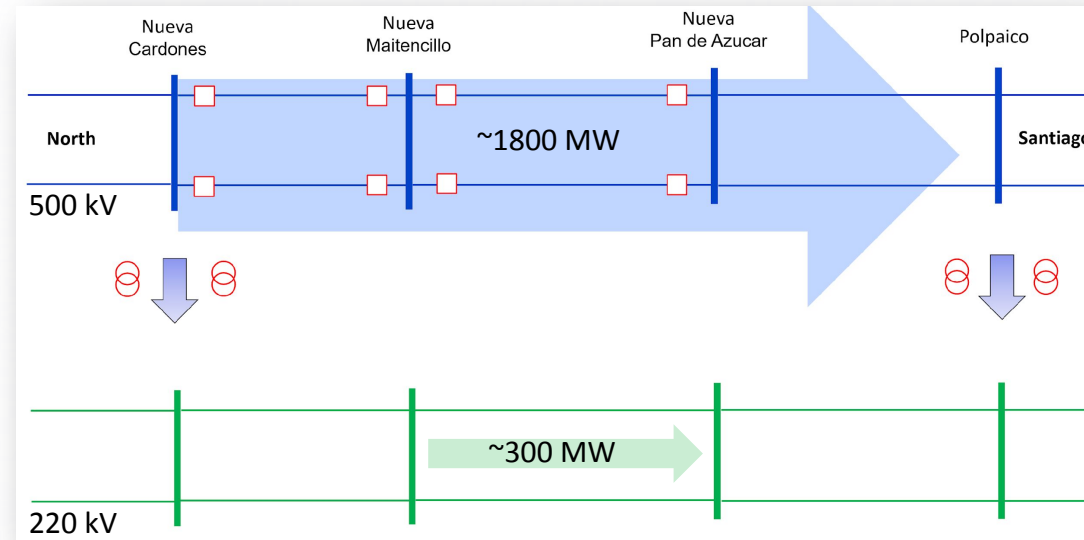


<https://www.entsoe.eu/news/2025/05/30/incident-in-the-power-system-of-north-macedonia-on-may-18th/>



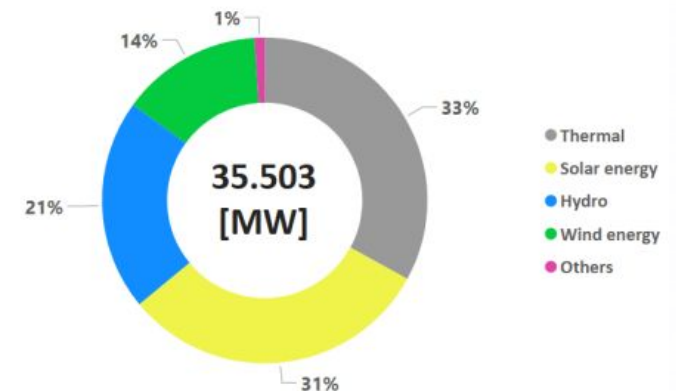
Chile 25th February 2025 - Summary

- ~11000 MW peak load (45% IBR)
 - ~3000 MW load in the North
- North to South (N-S) large power transfers across long series and shunt compensated 500 kV corridors
- Initial 2x 500 kV circuit tripped from 1800 MW N-S
- About 300 MW flowing N-S on 220 kV network
- System defense plans proved ineffective
- Limited N-2 real-time analysis capability



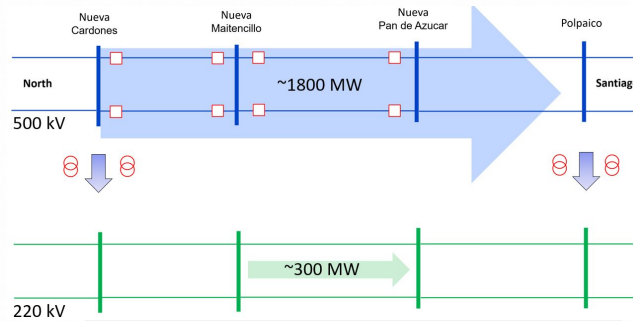
Overview of Chilean System

- Very long (>3000 km) and narrow system with 500 kV backbone
 - 500 kV backbone based on double circuit running on the same tower
 - Special protection schemes and defense plans to avoid total blackout
- Generation mix: coal-fired, CCGT, hydro and renewables
 - High penetration of renewables in the North and mining industry
- Majority of residential demand and high level of DER in the South



Event Timeline

Pre-Contingency to Restoration



Pre-Contingency N-S flows

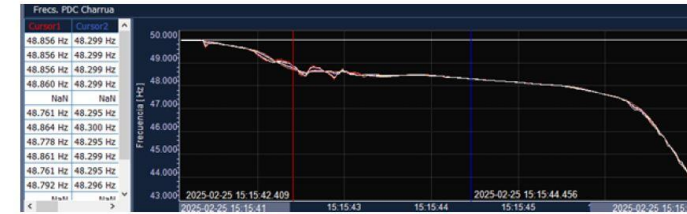
Operating at N-1 criteria per grid code
1800 MW N-S 500kV (90%), 300 MW 220kV
High IBR in North



Inadvertent Trip of 500kV

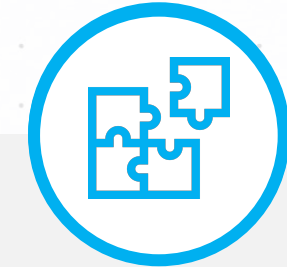
Operation of protection relays on 500kV
Troubleshooting on comms before event
Pushed flow to 220kV, then system separation

Isla Sur:



En la gráfica se demuestra que se superaron los escalones absolutos 2, 4, 5 y 6.

En cuanto al gradiente de frecuencia de los escalones (-0.6 Hz/seg), se observa en las imágenes que la frecuencia eléctrica presentó una disminución mayor a dicho ajuste para magnitudes de esta variable bajo los 49 Hz.

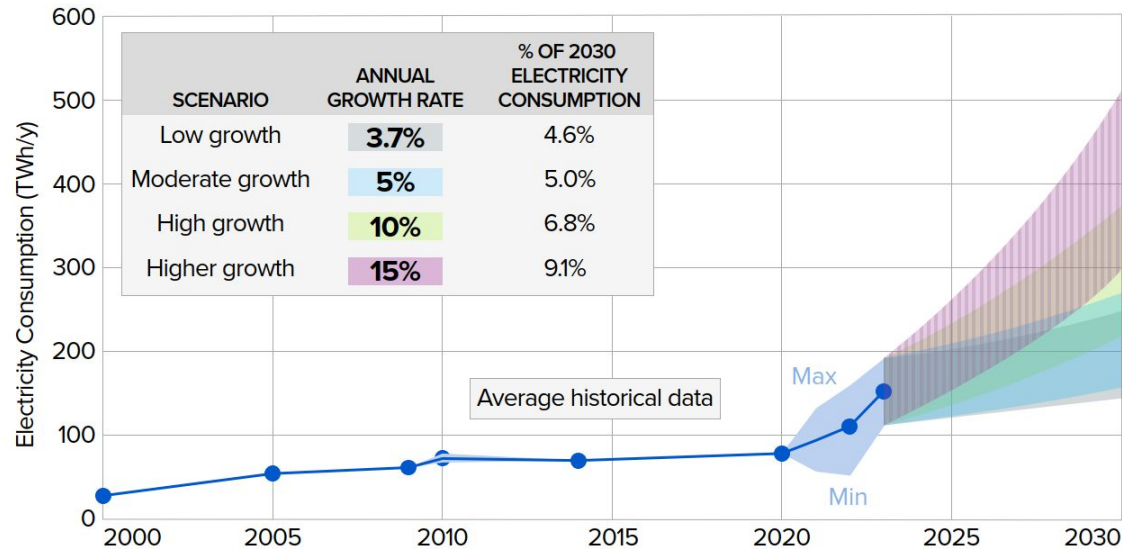


Restoration Challenges

Loss of comms with one Trans Owner
Issues with starting up of generators
Examples of collapsing islands

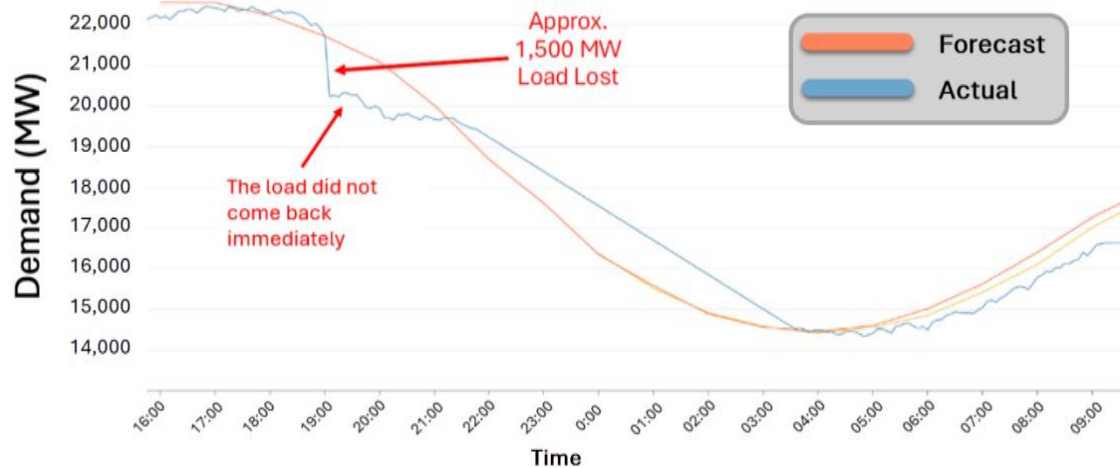
Cascading Event Starting with Tripping of 500 kV N-S line

Large Loads – Examples from the US



Significant New Large Loads Coming Online

- 100s MW or GW scale loads
- Load profiles can vary substantially
- Come online quickly (less than 3 years)



Potential for Rapid Disconnection

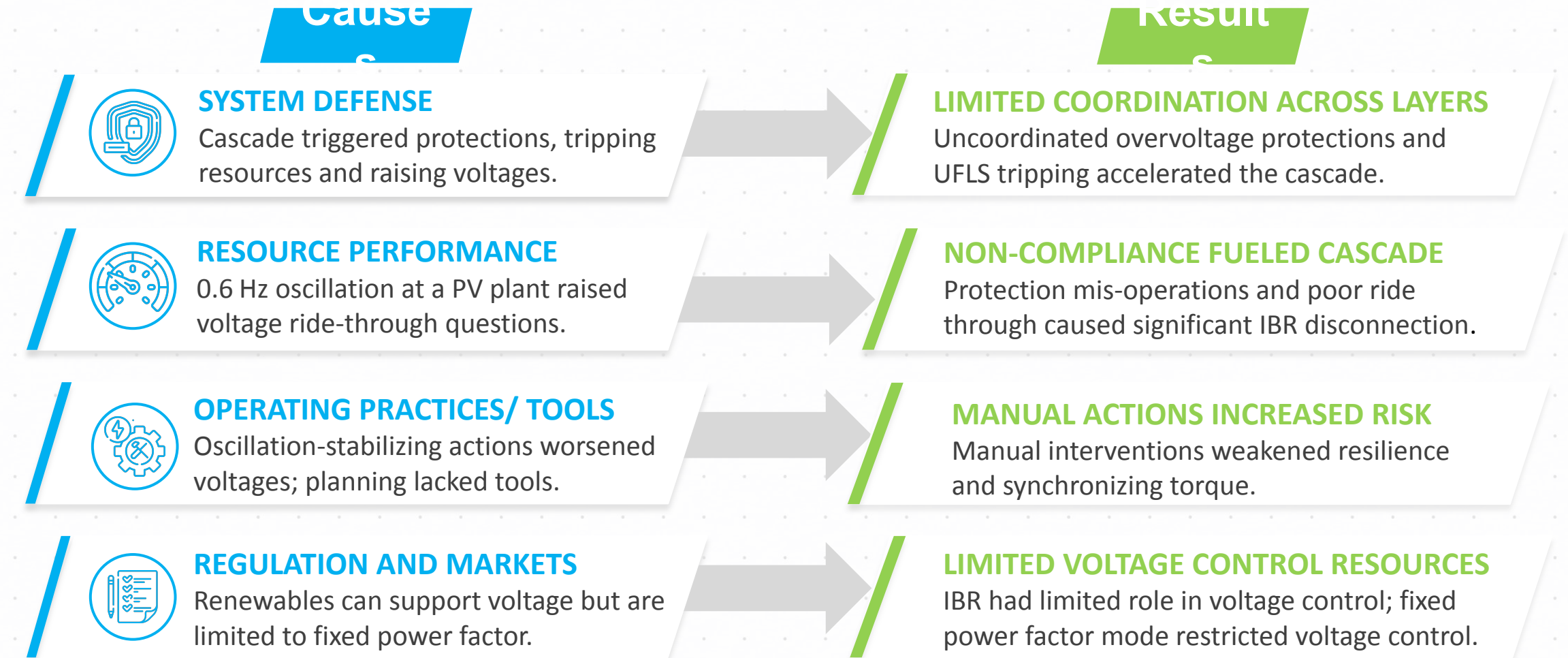
- Move to Uninterruptible Power Supply after a fault on the system
- NERC reports have shown significant disconnection of large amount of load



Where Next: Lessons Learned and Future Needs

Many Factors Drove Increased Grid Complexity, Precipitating Conditions for Blackout

Wide-area blackouts of large power grids are **never simple or driven by a single cause**—the case with the Iberian blackout.



Lessons for Global Power Systems

Key lessons from three levels reveal how actions, systems, and resources drove the events.

01 Exact Root Cause

Will be identified in reports at national and European level.

02 High IBR Operation Risks

- Oscillations and voltage management with high IBR
- Asset behavior and interconnection
- Situational awareness and impact of distributed resource

03 Universal Learnings

- Managing conflicting objectives
- Unstudied/new operating conditions
- Market, policy changes impact security
- Organizational models and data management

The 2025 Iberian Blackout and other events underscore how increasingly complex grid conditions, market misalignments, resource performance issues, and unforeseen events can strain system reliability.

Lessons Relate to Wider Trends Influencing Reliability

TIERS OF LESSONS

01 **Exact Root Cause**

Will be identified in reports at national and European level.

02 **High IBR Operation Risks**

- Oscillations and voltage management with high IBR
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03 **Universal Learnings**

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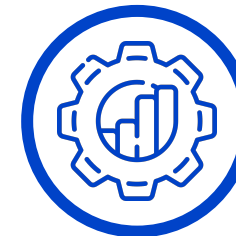
CRITICAL EMERGING TRENDS



**Increasingly Complex
Grid Conditions**



**Regulation/ Market
Misalignment**



Resource Performance



Unforeseen Conditions

Actions Needed to Address Reliability Trends

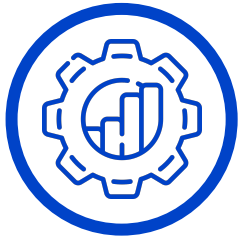
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Resource Performance

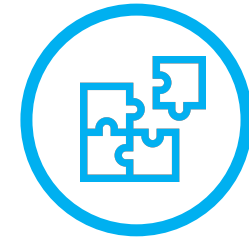


Unforeseen Conditions

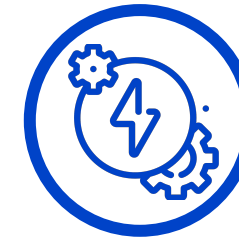
ACTIONS NEEDED



**Grid Vulnerability &
Risk Framework**



**Rapid Transition
Capability Model**



**Advanced Tools for
Operations & Planning**



**Advanced Training for
Grid Operations**



Rapid Adaptation of Grid Defense, Analytics and Resilience

Objective

Address the critical challenges of maintaining reliability and resilience amid rapid change in electric grids.

How

- Grid Vulnerability and Risk Framework
- Rapid Transition Model for Transmission
- Advanced Tools for High IBR Operations and Planning
- Advanced Training for Grid Operations

Highlights

3.5 Yr Duration

1st Deliverables in Year 1

Regional Risk Framework Studies

Advanced Data Tools To Support Event Analysis

Training to Address Complex Topics



Translating RADAR Insights into Action

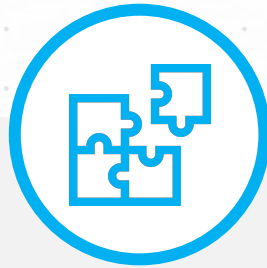
RADAR turns insight into action, aligning people, tools, and processes to strengthen grid stability.



Grid Risk

WS1: Grid Vulnerability & Risk Framework

Provides a structured approach to identify, assess, and anticipate emerging grid risks, helping organizations make proactive, informed decisions.



Process

WS2: Rapid Transition Model for Transmission

Offers a roadmap and best practices for modernizing transmission planning and operations to meet evolving grid demands.



Tools & Data

WS3: Tools for Emerging Tech Operations & Planning

Delivers sophisticated analytics, software, and workflows to manage complex, inverter-heavy grids efficiently and reliably.



People

WS4: Advanced Training for Grid Operations

Prepares operators with advanced skills and knowledge to handle dynamic conditions, complex scenarios, and ensure grid reliability.

Aligning People, Process, Tools and Data to Comprehensive Assessment of Risk



TOGETHER...SHAPING THE FUTURE OF ENERGY®